THE JOURNAL

OF THE

ROYAL AERONAUTICAL SOCIETY

(FOUNDED 1897 in succession to the ANNUAL REPORTS)

Edited for the Council by J. LAURENCE PRITCHARD, Fellow

No. 166 OCTOBER, 1924 VOL. XXVIII

NOTICES

Election of Members

The following Members were elected at a Council Meeting held on September 16th:—

Associate Fellows.—Mr. F. A. Kerry, B.Sc., Mr. C. J. Sanders, Major G. H. Scott, C.B.E., A.F.C., and Professor O. S. Sinnatt, D.Sc.
Student.—Mr. J. W. H. Barrett.
Foreign Member.—Mons. H. Faillant.

Chairman

Lieut.-Colonel H. T. Tizard, A.F.C., assumed office as Chairman of the Society for the year 1924-1925 on October 1st. Colonel A. Ogilvie, C.B.E., the retiring Chairman, becomes Vice-Chairman for the same period.

Forthcoming Arrangements

Thursday, October 2nd, 5.30 p.m.—In the Society's Library. Lieut.-Colonel H. T. Tizard, A.F.C., F.R.Ae.S.: "Common Sense and Aeronautics."

Thursday, October 16th, 5.30 p.m.—At the Royal Society of Arts. Dr. A. Rohrbach: "Large All-Metal Seaplanes."

Tuesday, October 21st, 5.30 p.m.—Council Meeting.

Thursday, October 30th, 5.30 p.m.—In the Society's Library. Major J. S. Buchanan, A.F.R.Ae.S.: "The R.Ae.C. Light Aeroplane Competitions."

Thursday, November 13th, 5.30 p.m.—In the Society's Library. Professor L. Bairstow, C.B.E., F.R.S., F.R.Ae.S.: "Skin Friction."

W. LOCKWOOD MARSH, *Secretary.*

Scottish Branch

The following programme of lectures for the season 1924-1925 has been arranged for the members of the Scottish Branch:—

1924.

Monday, 20th October.—Annual General Meeting, in the Royal Technical College at 8 p.m. Lecture by Air-Commodore F. C. Halahan, Director of Technical Development at the Air Ministry, on "Some Interesting Development Problems." Lord Invernairn presiding.

Tuesday, 11th November.—If circumstances permit, the Right Hon. Lord Thomson, Minister for Air, will be present at this meeting, and say something on "The Air Position in Britain To-day." Further particulars as to place and time will be circulated in the end of October, after Lord Thomson's wishes in the matter have been ascertained. The Right Hon. Lord Weir presiding.

Monday, 1st December.—Lecture in the Royal Technical College at 8 p.m., by Mr. F. T. Courtney, on "The Difficulties of Aeroplane Experimental Development." Mr. J. Howden Hume, President of the Institute of Engineers and Shipbuilders, presiding.

1925.

Wednesday, 28th January.—Lecture in the Royal Technical College at 8 p.m., by Sir Sefton Brancker, Director of Civil Aviation, on "The Relation Between Civil and Military Aviation." Professor Barr, LL.D., presiding.

Monday, 16th February.—Lecture in the Royal Technical College by Mr. George F. Luke, F.R.G.S., on "The Beneficent Effects Conferred on Civilisation by Aviation apart from the Carrying of Goods and Passengers." Mr. Harold Yarrow, C.B.E., ex-President of the Institute of Engineers and Shipbuilders, presiding.

Tuesday, 3rd March.—Lecture in the Royal Technical College at 8 p.m., by Mr. A. E. Hagg, of the De Havilland Aircraft Company, on "Control at Low Speeds." Professor Hudson Beare, D.Sc., Edinburgh, presiding.

Friday, 3rd April.—Annual Lecture to the Cadets of the Public Schools of Glasgow at 3 p.m., in the large hall of the Engineers' Institute, Elmbank Street, on "Airships Up-to-Date," by Major G. Herbert Scott, C.B.E., A.F.C.

Lecture at 8 p.m., in the small hall of the Engineers Institute, by Major Scott, on "The New Empire View of Airships and the Practical Possibilities Arising Therefrom."

W. Lockwood Marsh, *Secretary.*

THE ROYAL AERONAUTICAL SOCIETY

(SCOTTISH BRANCH)

FIFTH ANNUAL REPORT for Year ending 31st MAY, 1924

Executive

Chairman—The LORD INVERNAIRN OF STRATHNAIRN, F.R.Ae.S.

ARCH. BARR, D.Sc., LL.D., Westerton, Milngavie.
Captain DOUGLAS S. BARR, Anniesland.
Prof. HUDSON BEARE, D.Sc., Edinburgh University.
The Hon. Lord BLYTHSWOOD, Renfrew.
A. J. CAMPBELL, A.F.R.Ae.S., General Manager, Dalmuir.
Professor CORMACK, C.M.G., D.Sc., F.R.Ae.S., Glasgow University.
Prof. A. L. MELLANBY, D.Sc., Royal Technical College.
Capt. GRAHAM DONALD, D.F.C., Johnstone.
The Hon. the Marquis of GRAHAM, D.L., C.B., C.V.O.
Professor GORDON GRAY, D.Sc., Glasgow.
J. HOWDEN HUME, Glasgow.
Sir JOHN HUNTER, K.B.E., F.R.Ae.S., Glasgow.
Captain KINGWILL, Renfrew.
GEORGE F. LUKE, F.R.G.S., Glasgow.
The Right Hon. Lord ALNESS, P.C., LL.D., Edinburgh.
NOEL E. PECK, Glasgow.
Sir JOHN REID, D.L., A.F.R.Ae.S., Glasgow.
Maj. G. HERBERT SCOTT, A.F.R.Ae.S., C.B.E., A.F.C.
Lieut.-Col. L. H. STRAIN, D.S.C., O.B.E., Edinburgh.
W. STANCLIFFE SHACKLETON, Dalmuir.
His Grace the Duke of SUTHERLAND.
JAMES G. WEIR, C.M.G., C.B.E., F.R.Ae.S., Cathcart.
HAROLD E. YARROW, C.B.E., A.F.R.Ae.S., Glasgow.

The Executive Committee have pleasure in submitting their Fifth Annual Report, from which it will be seen that their activities have in no way been less than heretofore.

The cloud of depression which, owing to post-war finance, had caused Aviation to suffer so severely, probably more than any other branch of science, is gradually passing. Succeeding Governments which have come into power, while varying on many subjects, have all been unanimous with regard to the necessity of Great Britain having a well-equipped Air Force. Suitable grants have been made in this year's Budget and, for the first time since the War, our designers and constructors are once again busy on new and progressive designs, while it has been at last decided to give the Air Force a new machine to replace the now ancient D.H.9a.

Executive Committee

Events during the year which have been of interest are:—

1. The creation of the Imperial Airways Co., Ltd., which is an amalgamation of all the previous individual air transport companies, and which is subsidised by the Government to the extent of £1,000,000 spread over a number of years.

This Company has extended the air routes from this country, so that it is possible now to fly by regular service from England to Leningrad in the North, and to Rome in the South, and further extensions are being contemplated.

2. A great achievement has to be recorded in the Round Australia flight in which a distance of 8,568 miles were flown in 90 flying hours.

3. The report on Iraq by Air Marshal Sir John Salmond shows what useful work the Air Force has done in controlling that country without occupation. The Executive consider that this report is one which should be read by all our members, and copies will be sent to any who may desire to have them on application to the Honorary Secretary.

4. Another epoch-making flight has to be recorded in the achievement of Lieut. Pelletier d'Oisy, of the French Army, whose remarkable flight from Paris to Tokio is a record of rapid transit.

5. The efforts which have been made during the year to promote safety in flight have been of interest to the Executive, and it is hoped that progress in this direction will be made in the coming year, although the statistics of the Air Transport Co. for the last year are remarkable for their lack of accidents, considering the number of miles flown.

6. Great progress has been made this last year in the light 'plane, and the Executive is watching this movement with sympathetic interest. The competitions which are to take place in September should do much to popularise the low-powered aeroplane.

7. It is interesting that the Government are taking up again the question of rapid transport within the Empire, and that the use of airships has not been entirely overlooked.

The Airship Guarantee Co. are receiving assistance from the Government for the construction of a new airship of a capacity of 5,000,000 cubic feet, and plans are being drawn up for the construction of terminal and intermediate bases overseas, when it is hoped that a service will be inaugurated to enable two airships to operate safely between England and India. There can be no doubt that more rapid communications within the Empire will do much to unite the mother country more firmly to her dominions.

Propaganda and Education Committee

This Committee have to report that a useful series of lectures was carried out during the session, at which there was an average attendance of nearly 200. The following lectures were given :—

Thursday, 11th October.—In the large hall of the Engineers' Institute. Major-General Sir Frederick Sykes, K.C.B., C.M.G., on "Some Aspects of Aeronautical Progress." Lord Invernairn presided.

Thursday, 13th November.—In the Royal Technical College. Major F. T. Courtney on "The Practical Difficulties of Commercial Flying." Mr. James G. Weir presided.

Monday, 11th December.—In the Natural Philosophy Class-room of the University. Professor Gordon Gray on "A Complete Solution of Cloud and Night Flying Problems." Mr. George F. Luke, F.R.G.S., presided.

Tuesday, 29th January.—In the Royal Technical College. Mr. A. H. R. Fedden, of the Bristol Aeroplane Company, on "Radial Air-Cooled Aero Engines." Mr. Harold E. Yarrow, C.B.E., presided.

Tuesday, 19th February.—In the Royal Technical College. Mr. Allan E. L. Chorlton, C.B.E., on "The Beardmore 1,000 h.p. Engine." Professor Hudson Beare, D.Sc., of Edinburgh, presided.

Tuesday, 11th March.—In the Royal Technical College. Mr. W. H. Sayers, Technical Editor of "The Aeroplane," on "Gliders." Sir John Reid, D.L., presided.

Friday, 11th April.—In the large hall of the Engineers' Institute. Lecture by Mr. Handley Page to the Cadets of the Public Schools of Glasgow, on "Recent Developments in Civil Aviation." Professor Barr, LL.D., presided.

In the large hall of the Engineers' Institute, at 8 p.m., Mr. Handley Page on "Recent Progress in Aeroplane Design." Colonel Strain, of Edinburgh, presided.

The Society was fortunate in having Mr. Handley Page for the annual lecture to the Cadets, at which over 400 were present.

Regarding the work among the students of the University and the Technical College, the Honorary Secretary's efforts have again met with marked success. All the engineering classes in the University and the Royal Technical College were addressed by him, the students in these numbering over 1,000.

The number of names of engineering students now secured during the last four years, who are taking an interest in Aeronautical Science, and who may later devote themselves to it, amounts to 1,530, and the names and home addresses of these are available, of whom several hundreds possess the B.Sc. degree.

This useful work is one which could have been done by no other Society in Glasgow, and the thanks of the Society are due to Professors Cormack, Gordon Gray, Mellanby and Goudie for their cordial co-operation and goodwill in the matter.

The Society has followed with much interest the work of the Royal Air Force Reserve School at Renfrew Aerodrome through Captain Kingwill, who has joined the Executive.

The proposals of the Government with regard to the formation of a Home Defence Force are being followed with interest, and there is no doubt that the Society will be able to render valuable assistance to the Government in the recruiting of such a force when the time is ripe.

In regard to the movement for a School of Research, the Society believes that probably in no other centre does the material exist ready to hand of so fine a quality of men for the nucleus of such a School of Research as in Glasgow. This is due not only to the proximity of the University, but also to the fact that the Renfrew Aerodrome is so conveniently situated and practical training at Dalmuir is within easy reach. No doubt these facts will be taken into account by the Air Ministry in any real scientific programme for aviation development they may make in the near future.

Finance Committee

This Committee has to report that the subscriptions for the year amounted to £161 10s. 0d., the total income of the Society being £176 13s. 0d. To this the balance of the Initial Establishment Fund must be added to show the amount of funds available. The outlays for the year were £259 11s. 7d., and the balance in hand at 31st May was £232 11s. 4d.

The Society has now been in existence for five years, and has been able to weather the after-war reaction, and it is possible that with the funds in hand the Society will be able to meet their liabilities for another year. There can be no question that the work which the Society has done has been of immense value in keeping alive the steady flame of interest in aviation in Scotland. Next year it may be necessary to appeal once again to those generous members of the Executive and others who so kindly came forward five years ago and raised the Initial Establishment Fund. In the meantime it should be the duty of every member of the Society to endeavour to secure the adhesion of at least another member, so that the annual income from subscriptions may be increased. If this were done, it seems probable, in view of the present revival of interest in aviation, that in

three or four years the Society will be able to carry on its good work by means of the subscriptions alone.

INVERNAIRN, *Chairman.*
J. BUYERS BLACK, *Hon. Secretary.*

THE ROYAL AERONAUTICAL SOCIETY (SCOTTISH BRANCH).

Abstract of Accounts for the Year ended 31st May, 1924.

RECEIPTS.

	£	s.	d.	£	s.	d.
Balance of Funds as at 31st May, 1923				315	9	11
Annual Subscriptions received				161	16	0
Interest on Glasgow Corporation Mortgage	5	7	11			
Refund of Income Tax	8	9	1			
				14	17	0
				£492	2	11

EXPENDITURE.

	£	s.	d.	£	s.	d.
Miscellaneous Expenses re Lectures	38	8	8			
Printing	6	18	9			
Typewriting Supplies, Stationery, etc.	6	0	8			
Postages, Telegrams and Telephone Calls	19	7	6			
Advertising	4	16	0			
	£75	11	7			
Honorary Secretary's Expenses:—						
1. Travelling Expenses	£2	10	0			
2. Clerical Assistance	81	10	0			
3. Allowance for use of Office, Office Expenses and Typewriters	100	0	0			
	184	0	0			
				259	11	7
Balance of Funds on Hand:—						
£200 5 per cent War Stock cost	201	6	0			
Balance in bank on Current Account	31	5	4			
				232	11	4
				£492	2	11

Audited and found correct.

(Signed) J. WYLLIE GUILD & BALLANTINE, C.A., Auditors.

Glasgow. August 18th, 1924.

THE ROYAL AERONAUTICAL SOCIETY

WILBUR WRIGHT LECTURE, MAY 29th, 1924.

The Wilbur Wright lecture was delivered by Lieutenant-Colonel H. T. Tizard, A.F.C., a Fellow of the Society, at the Royal Society of Arts, John Street, Adelphi, on May 29th, 1924. The chair was taken by Colonel Ogilvie, who, in introducing the lecturer, said:—

Before asking our Lecturer to give us his paper, I should like to refer to the man in whose memory this lecture was instituted.

From the beginning of their experiments the Wrights had kept in close touch with the Aeronautical Society of Great Britain, amongst whom there were many firm believers when most of the world was sceptical.

When Wilbur died in May, 1912, a commemoration fund was suggested by Mr. Griffith Brewer, who was, amongst us all, their most intimate and close friend. The Society supported the proposal with enthusiasm, and this annual lecture, which is the most important event of our session, is the result.

Since 1912 the position of the Wrights has greatly altered and they are everywhere acknowledged to be the real originators of the flying machine. As to this I cannot do better than quote Sir Walter Raleigh in his book, "The War in the Air":—

> "New inventions are commonly the work of many minds, and it would be easy to name at least half a dozen men to whose work the Wrights were indebted. But these were tributaries; the main achievement belongs wholly to the Wrights. Their quiet perseverance through long years, in the face of every kind of difficulty, is only a part of their distinction; the alertness and humility of mind which refused all traffic with fixed ideas, and made dangers and disappointments the material of education, is what stamps them with greatness."

In calling upon Colonel Tizard, there is no need for me to introduce him to the Society for whom he has done so much valuable work, particularly by his paper on "Aeroplane Testing" in 1917.

At the commencement of the war Colonel Tizard was a Lecturer in Chemistry at Oxford; at the end of it he was in charge of all experimental work for the Technical Department. That is an indication of his capacity and, if I may venture to do so, I should attribute his success to his steady determination to get at the real facts of any case before coming to a decision. In aeronautical circles most of us have a tendency to jump too quickly to conclusions and we must acknowledge the great debt which aviation in this country owes to Colonel Tizard as much for his sound commonsense as for his brilliant scientific achievements.

From his present position in the Department of Scientific and Industrial Research and as a member of the Aeronautical Research Committee, Colonel Tizard is able to take an unprejudiced view of the technical aspect of present-day aviation, and on the subject of "Fuel Economy in Flight" the Society is awaiting his views with particular interest.

As you know, I have endeavoured during my period of office as Chairman to waste as little of your time as possible, but this is a special occasion and I hope you will forgive me for this short speech.

FUEL ECONOMY IN FLIGHT

BY LIEUTENANT-COLONEL H. T. TIZARD, A.F.C., FELLOW.

Fuel consumption in flight is dependent on three main factors—the aerodynamic efficiency of the aeroplane, the thermal efficiency of the engine, and the efficiency of navigation, which entails a study of the most advantageous height, speed and direction of flight under any conditions of wind. Fuel consumption is therefore the ultimate measure of the overall efficiency of the complete aeroplane, the pilot, and the organisation; its complete study would require far more time than can be given to it in a single lecture. I propose, therefore, to confine myself to fairly general considerations, with particular reference to the commercial aeroplane. There have been distinct advances in the direction of fuel economy in flight since the war period, but even now the weight of fuel carried in a commercial machine operating over the comparatively short London-Paris route of 230 miles and capable of a cruising speed of 100 miles per hour is approximately half the full paying load carried, so that a reduction of the fuel load by 40 per cent., which is by no means outside the range of possibilities, would increase the paying load by 20 per cent., other things being equal. Fuel economy is thus a matter of first importance, not to be measured only by a saving in the fuel bill.

I have often heard it stated that the cost of fuel is such a small proportion of the total cost of a commercial service that a saving in the fuel bill is not of any great importance. I do not quite share this view. Firstly, the cost of fuel appears from such figures as are available to be as high as 20 per cent. of the total annual charge under all heads; and secondly one might appreciate the argument if the possible savings on the fuel bill were only a small proportion of the profits of an air transport service, but when they may be a large proportion of the losses, the case is very different.

A considerable amount of experimental work on the fuel consumption of aeroplanes was carried out at Martlesham Heath during the war—unfortunately with somewhat imperfect instruments. The subject was also examined theoretically both there and elsewhere, while recently Mr. Cowley has taken up the whole question of economic flight again at the request of the Air Transport Sub-Committee of the Aeronautical Research Committee. I was somewhat surprised at the subject of fuel economy in flight being re-opened at the time, but the general view was that the previous results were not generally accessible. I thought, therefore, that this would be a suitable opportunity to bring the subject up to date in such a way as to make the results accessible to those chiefly interested. I confess that by the time I had finished writing my lecture and compared the conclusions with actual commercial practice, I was confirmed in my original doubts as to whether I could say anything of value which was not already well known to designers. However, having committed myself, I must do the best I can in the allotted time.

To treat the subject adequately, one wants to be endowed with a kind of intellectual squint. One eye must be firmly fixed on the strictly scientific aspects, the other must wander off to a contemplation of practical realities. The worst of such an endowment is that, far from the result satisfying both the scientific and practical world, there is a great risk of all parties finding it unattractive.

The problem of fuel economy in flight may be divided into two distinct parts, namely :—

(*a*) What are the principles governing the most economical use of an aeroplane in flight, having regard to the weather conditions.

(*b*) What are the principles underlying the design of aeroplanes to secure maximum efficiency of operation.

The first part can be treated on strictly scientific lines. The second part, to be treated fully, requires a knowledge of all manufacturing and operating costs. I shall therefore deal mainly in the first part; but it will be seen that its consideration leads on naturally to a review of some of the more important scientific questions affecting economical design.

The problem can be most simply approached in the following way.

If D is the resistance or drag of an aeroplane in flight at any indicated air-speed $\sigma^{\frac{1}{2}}V$, the work done per hour is proportional to $D \times V$, where V is the speed in miles per hour. The brake horse-power necessary is proportional to $D \times V/\eta$, where η is the airscrew efficiency. The fuel consumption per hour is therefore proportional to $D \times V/\eta \times C$, where C is the consumption in lbs. of fuel per h.p. hour. Hence the consumption per air-mile is proportional to $D \times C/\eta$. If D is expressed in lbs. weight, the proportionality factor is $88/60 \times 550 = .00267$, and the fuel consumption in lbs. of fuel per air-mile is $.00267 \times D \times C/\eta$.

It can easily be shown that the range of an aeroplane in level flight at any indicated air-speed is practically independent of the height. In the first place, D depends only on $\sigma^{\frac{1}{2}}V$, whatever the height, assuming no change in weight. Further, the value of V/n, where n represents the rate of revolution of the airscrew (or engine), is also independent of height for a constant indicated air-speed. Hence the propeller efficiency "η," which is a function of V/n, is independent of height. It only remains, therefore, to consider how far the minimum fuel consumption per b.h.p. hour varies with height under these conditions. There is no reason to suppose that the minimum consumption per *indicated* h.p. hour varies appreciably over the range of torque and engine revolutions corresponding to a range in air-speed of, say, 70 to 120 m.p.h. Hence, since

$$\text{B.H.P.} = \text{I.H.P.} \times \text{mechanical efficiency},$$

what we have to consider is how far the mechanical efficiency varies with height if $\sigma^{\frac{1}{2}}V$ is constant. The power absorbed in overcoming piston friction, bearing friction, pumping losses, etc., depends on two factors, torque and engine-speed. Opinion is still divided on the question of the extent of the variation with torque, but this does not affect the present problem, for if we express the torque conventionally in terms of brake mean effective pressure on the piston, we can write

$$\text{B.M.E.P.} \times n = \text{constant} \times D \times V/\eta$$

$$\therefore \text{B.M.E.P.} = \text{constant} \times D/\eta \times V/n$$

and is therefore independent of height if $\sigma^{\frac{1}{2}}V$ is constant. The speed of revolution, however, varies considerably, for it is proportional to the true air-speed V and therefore inversely to the square root of atmospheric density, *i.e.*, to $\sigma^{\frac{1}{2}}$. The engine revolutions will thus be about 25 per cent. higher at 15,000 feet than at the same air-speed near the ground. If the frictional losses are also expressed in terms of mean effective pressure, the mechanical efficiency =

$$\text{B.M.E.P.}/\text{I.M.E.P.} = \text{B.M.E.P.}/(\text{B.M.E.P.} + \text{F.M.E.P.})$$

and the consumption per b.h.p. is proportional to

$$(\text{B.M.E.P.} + \text{F.M.E.P.})/\text{B.M.E.P.}$$

The mean effective pressure corresponding to the mechanical losses is found to increase nearly, but not quite, in proportion to "n" when the engine is not throttled. Hence at 15,000 feet it will be not more than 12 per cent. (or about 1.5 lbs. m.e.p.) higher than at the same air-speed near the ground, if we ignore the higher pumping losses near the ground due to the fact that the engine is throttled. In fact, these higher pumping losses slightly exceed the higher frictional losses at the greater height. From a consideration of the available data, it appears that even in the worst case the consumption per b.h.p. when flying level at two-thirds the maximum engine-speed near the ground should not be more than 2 per cent.

higher than when flying level at the same air-speed at 15,000 feet. For all practical purposes it follows that *the range of any given aeroplane in still air depends only on the indicated air-speed, and is independent of height.* This conclusion is independent of any assumption as to the decrease in maximum engine power with height. The variation of engine power with height affects the performance of an aeroplane but not its range at any indicated air-speed.

By flying high on a calm day, time but not fuel can be saved if there is no wind. The prevalent idea that it is more economical to fly high seems to be due to the following consideration. The maximum range per lb. of fuel of an aeroplane is inversely proportional to its weight. By climbing to a great height at the start of a long flight, a certain weight of fuel is converted into potential energy, which can be partially used effectively by a glide at the end of the flight; hence a saving is effected owing to the fact that it costs nothing to carry potential energy about, but something to carry fuel about. But this theoretical saving is only very small. The possible small advantages in flying high would be entirely negatived if the wind at the height in question were one or two miles an hour faster in a contrary direction than at ground level. In view of the fact that the differences are of this order, the inquiry as to the best height to fly in still air is not worth pursuing in great detail. In practice, as still air is a phenomenon more familiar to the scientist than to the pilot, the wind is the chief factor in determining the most economical height to fly. As the strength of the wind generally increases with height, the average rule must be that when flying against the wind it pays to keep as low as possible, and when flying with the wind it pays to keep as high as possible, provided the consumption per b.h.p. hour is always kept to the minimum; but on any particular occasion the decision of the best height to fly must be determined by the actual meteorological conditions.

It is somewhat unfortunate that the conclusion that the air range of an aeroplane is sensibly independent of height has never been put to a satisfactory practical test. The experiments made at Martlesham Heath during the war certainly seemed to indicate quite a definite increase in range with height—more than one would expect by taking loss of weight due to fuel consumption into account—but unfortunately these results cannot be regarded as sufficiently reliable, partly because the hand-control provided for adjusting the fuel flow was often not sufficient to reduce the fuel consumption of a throttled engine to the minimum, and partly because of the imperfections in the flow-meters employed. In the years since the war no one has yet succeeded in producing a satisfactory instrument, so far as I know, and for experimental purposes it will probably be better, if any further work on the subject is done, to rely on a more direct method by actually observing the time necessary for a given volume of fuel from a special auxiliary tank to be consumed. But for practical purposes of air transport, it might be worth while pointing out here that it is not necessary for a petrol flow-meter to be strictly accurate in its readings for utility. An instrument which would indicate effectively when the minimum consumption was reached would be sufficient for all ordinary purposes.

In determining the variation in the range of an aeroplane with the indicated air-speed, it is therefore sufficient for our purposes to consider only the conditions of level flight near the ground, say, at standard atmospheric density. The results so obtained will be applicable to any height.

Of the three quantities D, C and η, the variation of drag with speed is usually the most important, and the variation of the airscrew efficiency the least. Indeed, if the airscrew is so designed that the maximum value of I'/n at the maximum speed in level flight is some 5 per cent. over the value at the point of maximum efficiency, which appears to be the best practice at present, then the variation in efficiency over the whole normal range in level flight will probably be less than

2 per cent. Hence it is not worth while taking into account variations in airscrew efficiency in a general consideration of economical flight. We can assume the efficiency to be constant without affecting any of the conclusions to be drawn.

The relation between the rate of fuel consumption of the engine and the speed of an aeroplane is so intimately bound up with the characteristics of the aeroplane that at first sight it might seem a matter only to be discussed in relation to a particular engine and aeroplane; but here again general considerations help in getting some idea of what to expect. A good deal of importance is sometimes attached to the results of observations of fuel consumption, at various speeds, of

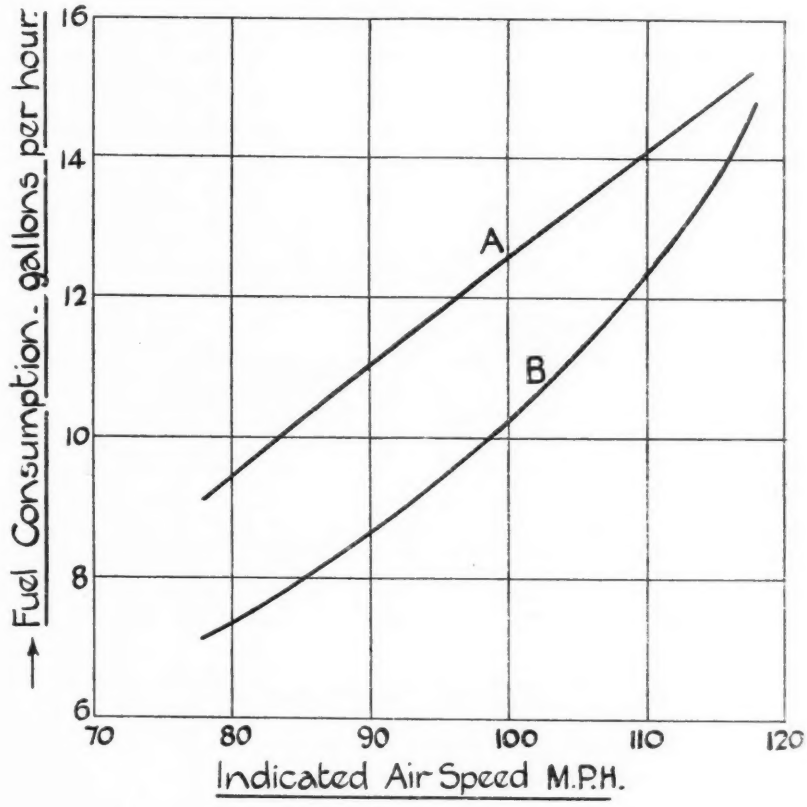

FIG. 1.

a throttled engine coupled to a dynamometer, but for many reasons it is doubtful whether such results can be applied with any confidence when estimating the fuel consumption of a throttled engine in flight. In the first place it must be remembered that no carburettor delivers under all conditions a constant proportion of fuel and air; nor, indeed, is a constant proportion required for the whole range of engine-speed. At very low, idling speeds, the proportion of fuel must be higher than at maximum speeds, both because of the comparatively slow rate of combustion and because it is necessary, owing to the inertia of the liquid, to provide a rich mixture at slow speeds, in order that acceleration shall be rapid. Rapid

and certain acceleration from slow speeds is of such overwhelming importance in flying, from the point of view of safety, that the tendency is always to err on the rich side when the engine is throttled. We may say, indeed, that there are two main requirements to be borne in mind when adjusting a carburettor; firstly, rapid acceleration from slow speeds, and secondly minimum consumption at maximum power. The minimum consumption at maximum power is slightly greater than the minimum consumption of a slightly throttled engine, because in the latter case one can afford to operate on a slightly weaker mixture. The science of designing and adjusting a carburettor for an aircraft engine depends on meeting these two requirements consistently with a reasonably low consumption from, say, half to full speed. It is a science which has progressed very con-

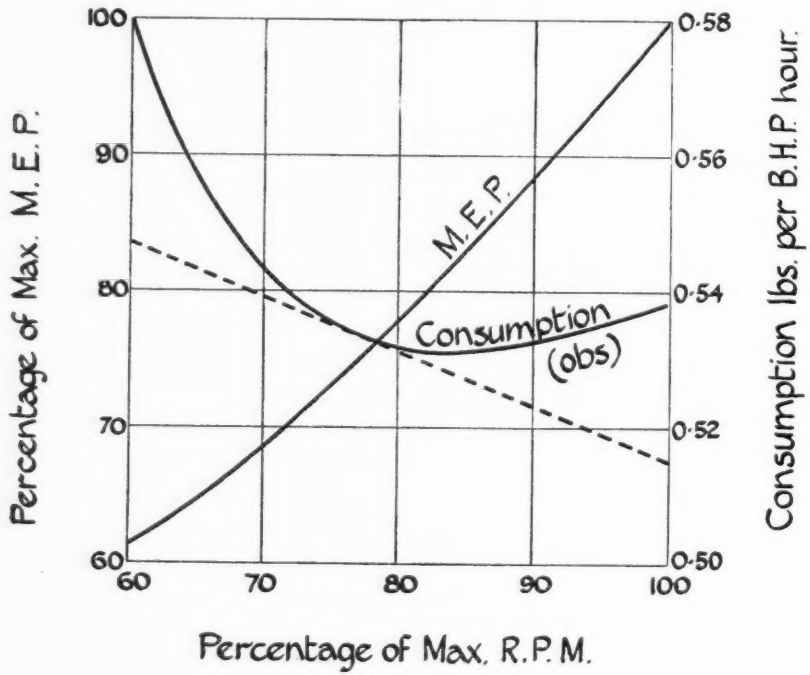

FIG. 2.

siderably in the last few years. At the beginning of the war it was little understood, mainly due to the fact that necessary instruments were not available, and it may be of interest here if I put on record some results obtained in 1917. Fig. 1 shows the fuel consumption in level flight at low heights of a D.H.4 machine fitted with a B.H.P. engine. The upper curve A was obtained with a carburettor adjusted by the makers and fitted unchanged. The lower curve B was obtained with a carburettor fitted and adjusted at Martlesham Heath. In neither case was any form of adjustment made in flight. It will be seen that whereas the consumption at full speed only differed by about 3 per cent., the consumption at low speeds was 30 per cent. higher in one case than in the other. I do not pretend that such differences are found nowadays. Fig. 2 represents the actual results of a bench test in which the carburettor was adjusted to deliver the minimum amount of fuel throughout the range consistent with meeting two main

requirements mentioned above. The dotted line represents approximately what the consumption would be if it were adjusted to the minimum without regard to the other requirements. It is only possible to adjust a carburettor to give automatically the most economical results over a small range of torque at ground level.

Instead of the ordinary consumption curve of a throttled engine, it would, in my opinion, be of more value if the following observations were taken. Firstly, the actual petrol consumption, without special adjustment of the carburettor, at (*a*) 90 per cent. of the maximum speed and 85 per cent. of the maximum torque, and (*b*) at 70 per cent. of the maximum speed and 70 per cent. torque; and secondly, the *minimum* consumption under the same conditions, observed by reducing the petrol supply by adjusting the "altitude" control. The range of speed and torque corresponds to the normal range in level flight of a commercial aeroplane, and the observation would not only give a truer indication of the minimum fuel consumption to be expected in flight, but would also test the accuracy of the setting of the carburettor, and give a valuable check on the mechanical efficiency of the engine.

But apart from the question of the accuracy of carburettor adjustment, there is a further more fundamental reason why bench figures for the fuel consumption of a throttled engine cannot be applied without question to flight conditions. To do so implies that the characteristics of an aeroplane as a dynamometer correspond exactly to the characteristics of the particular kind of dynamometer used in the bench tests. This is obviously untrue. To illustrate this point I show in Fig. 3 some special cases. The upper curves represent the change in fuel consumption per b.h.p. hour over a range of air-speed from full to half speed. In case (*a*) in the figure it is assumed that the drag of the aeroplane is proportional to the square of the air-speed. In case (*b*) it is assumed that the drag is constant. The variation of engine torque (expressed as B.M.E.P.) with speed under these conditions must obviously be very different. In the first case the torque at half the maximum air-speed is only a quarter of the maximum torque, and in the second case it is 76 per cent. In the second case, therefore, the engine must be operating at a far greater mechanical efficiency than in the first case, and the petrol consumption per b.h.p. is correspondingly lower. As a matter of fact, if the drag is nearly constant, the change in petrol consumption per b.h.p. is very small over this range in speed. The two cases chosen are extreme, of course, but at the same time they may be approached very nearly in practice. The first case corresponds to that of a high-speed aeroplane, the second case to that of a comparatively low-speed aeroplane of small body drag. The average aeroplane is represented by the dotted lines, which depict the conditions to be expected when the maximum speed of an aeroplane is twice its minimum speed in level flight. The minimum torque in such a case is roughly 64 per cent. of the maximum, and the consumption per b.h.p. hour at the point of minimum drag is only 7 per cent. above the figure at maximum power. This may be considered the limit for all conditions of commercial flying.

Turning now to the more important question of the variation of drag with speed, the first matter of interest is to estimate the maximum range in still air. This occurs at such an air-speed that the drag is a minimum, or nearly so.

The drag of an aeroplane is made up of the wing drag, which is a function of V/V_0, V being the air-speed and V_0 the minimum air-speed in level flight, and of the body drag, which is proportional to σV^2. In Fig. 4 the wing drag for R.A.F.15 (biplane) and the body drag are shown plotted against V^2/V_0^2. Assuming no variation in the type of wing, the curve for wing drag will be unaltered by a change in loading (or V_0) caused by a variation in wing area, but the slope of the line representing the body drag will depend on V_0, since the body drag depends only on the speed, not on the ratio of the speed to the minimum speed. On the other hand, if the wing area is kept constant and the change in V_0 is effected by

a change in the weight carried, *e.g.*, by loss of fuel during flight, the curves are unaltered; W becomes the new weight W', and V_0 the new minimum speed V_0'. The line drawn in the figure corresponds to the average body drag of a fully loaded

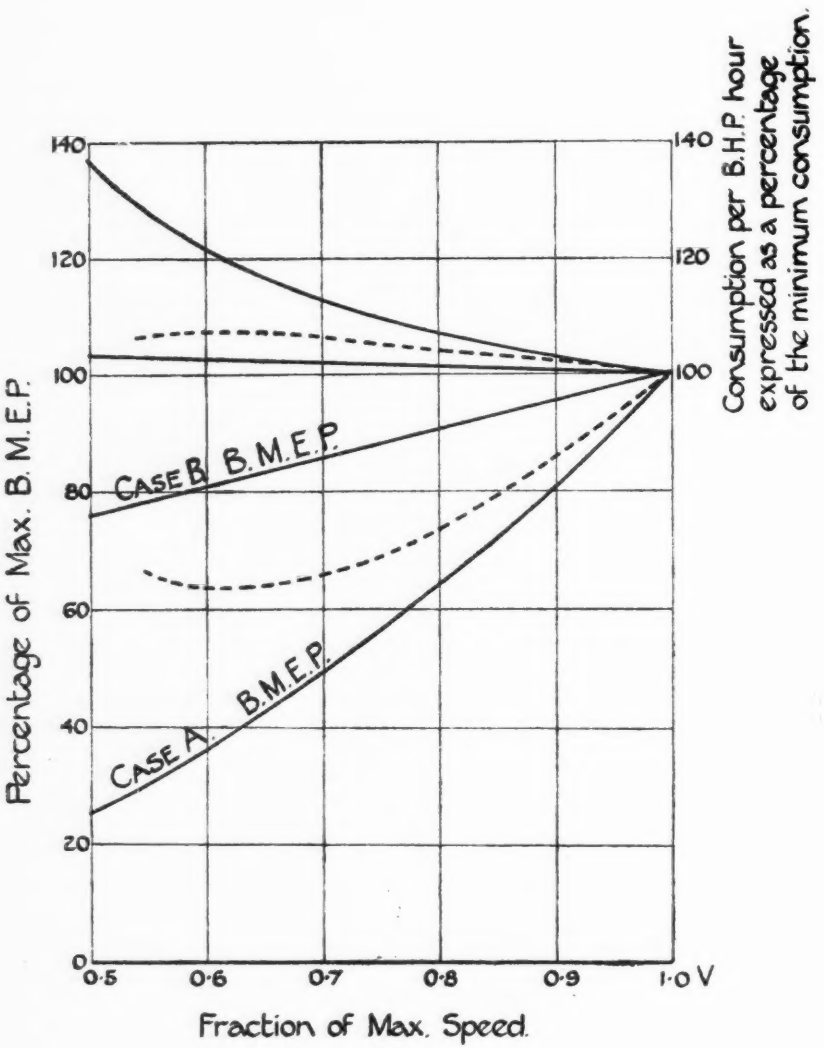

FIG. 3.

aeroplane of the war period, the loading being assumed to be 7 lbs. a square foot of wing area.* The upper curve shows the sum of wing and body drags. It is practically the same as the average curve given by Bairstow in his Applied Aero-

* Under these conditions V_0 is about 50 m.p.h.; the body drag at 100 m.p.h. $(v^2/v_0^2 = 4)$ is taken as $= 0.1\,W$.

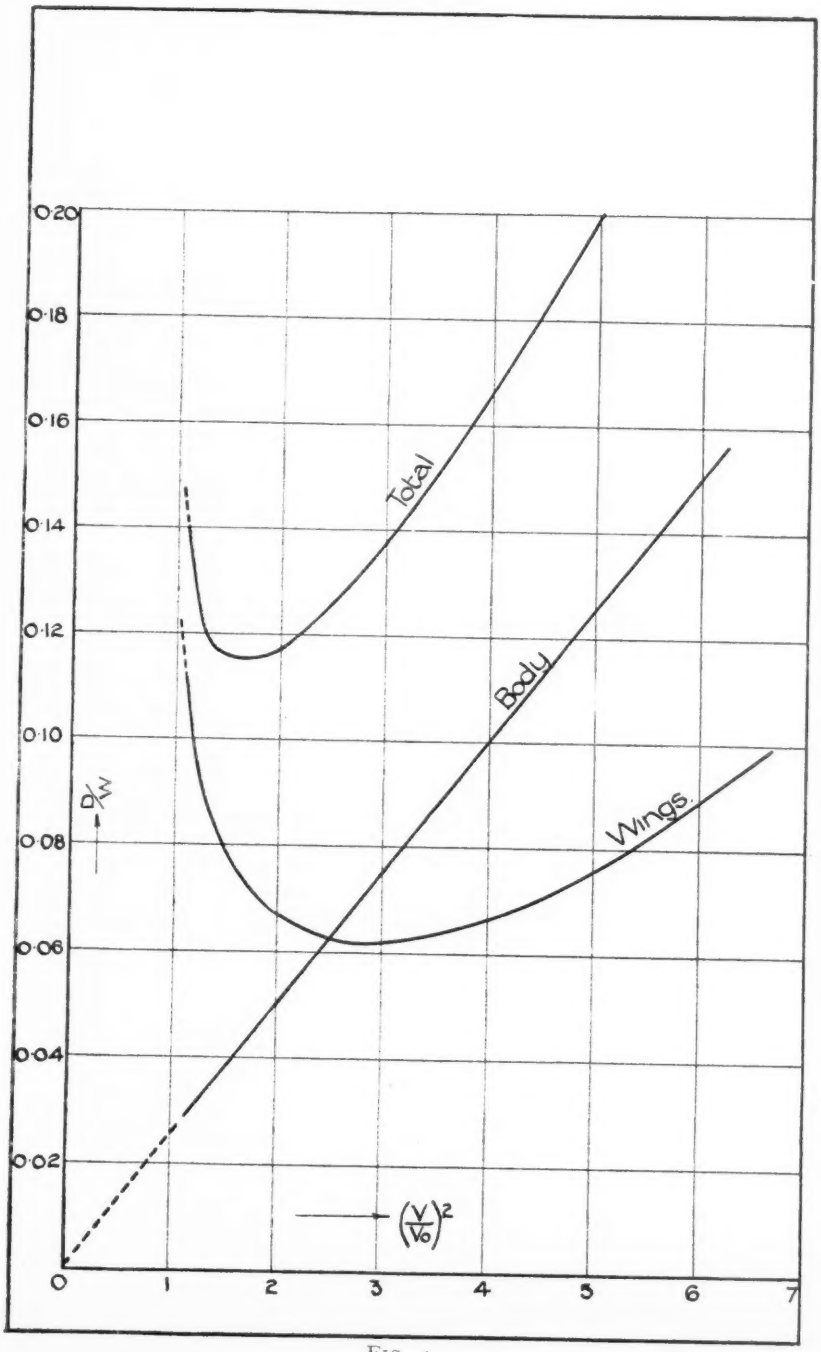
0·20
0·18
0·16
0·14
0·12
0·10
0·08
0·06
0·04
0·02
D/W
Total
Body
Wings
$\left(\frac{V}{V_0}\right)^2$
0
1
2
3
4
5
6
7

FIG. 4.

dynamics (p. 399), although it is plotted on a different basis. The minimum drag occurs at an air-speed = 1.2 to 1.3 times V_0, and is equal to $0.115W$, where W is the weight of the fully loaded aeroplane.

If we assume an airscrew efficiency of 75 per cent., and a consumption per h.p. hour of 0.60 lbs. (corresponding to 0.56 lbs. per h.p. hour at full throttle), the fuel consumption in lbs. per mile at this speed will be

$$.00267 \times 0.115W \times 0.60/0.75 = .00025W \text{ lbs. per mile,}$$

and the number of air-miles travelled per gallon of fuel will be

$$7.2/.00025W = 29{,}000/W.$$

or approximately 13 ton-miles per gallon. The average figure I took during the war as a result of a large number of tests was $28{,}000/W$, this range being exceeded by the more efficient machines developed towards the end of the war period. Some of the results are given in the following table:—

TABLE I.

Machine.	Weight fully loaded.	Measured maximum range in miles per gal. of petrol.	$28000/W$.
Sopwith Camel (110 Le Rhone)	1408	20.0	20.0
Sopwith Camel (150 B.R.)	1508	19.0	18.5
Bristol Fighter (Rolls Royce)	2780	10.2	10.1
Martinsyde (160 Beardmore)	2460	11.0	11.3
D.H.4 (Siddeley B.H.P.)	3234	9.7	8.7
D.H.4 (Eagle Rolls Royce)	3472	9.2	8.0
D.H.9A (Liberty)	4220	7·3	6.6

The V.1500 Handley Page, loaded to 28,000 lbs. total weight, also had a range of a little over one mile per gallon at full load, thus agreeing with the approximate formula. It will be noticed that the machines with rotary engines show up favourably in spite of the lower mechanical efficiency of these engines due to windage losses. This must be attributed largely to good fuel distribution. It will also be noticed that the machines with the highest range/weight ratio in the above table are the highly-loaded machines. This increase in range is not to be connected with the high loading; on the contrary the higher the loading the lower is the maximum range in still air, other things being equal. The improvement is to be attributed to lower body resistance and more efficient engines. But even now a figure of 13-14 ton-miles per gallon may be taken as the average performance of a modern aeroplane. Professor Bairstow gives this figure as representing the fuel consumption of the light aeroplane, while on the other hand it almost exactly corresponds to the figure arrived at by Mr. Cowley in a detailed analysis of the D.H.34 commercial machine of 7,200 lbs. total weight.

The figures given in the table refer to the fully loaded machine at the start of the flight. At the end of the flight the maximum range per lb. of fuel will be $W/(W-w)$ times the range per lb. of the fully loaded machine, w being the weight of fuel carried. The average range per lb. of fuel is $W/(W-w_2)$ times the range of the fully loaded machine, this expression differing by a negligible amount from the more exact expression obtained by integrating over the whole path. The most economical speed is, of course, lower at the end of the flight than at the beginning, since V_0 is smaller, but the drag varies so little over a fairly wide range of speed near the minimum point that in practice we can get the maximum range by keeping the air-speed constant throughout at about 20 per cent. higher than the landing speed of the fully loaded machines. At high speeds, on the other hand, the range at any definite air-speed is independent

of loss of weight due to the gradual consumption of fuel. If the speed is over 2.3 times the landing speed ($V^2/V_0^2 = 5.3$) the total drag (wings and body) is proportional to σV^2, and does not alter with the weight. At speeds higher than 1.3 V_0 the drag increases, and at the same time the fuel consumption per h.p. hour decreases. The net effect is that the air-range decreases, but not so much as would be expected if the change in drag alone were taken into account. Thus, if we assume V_0 to be 50 m.p.h., which is the minimum level speed of an aeroplane loaded to 7 lbs. per sq. ft., the drag when $V = 100$ [*i.e.*, $(V/V_0)^2 = 4$] is .166 W, *i.e.*, 45 per cent. more than the minimum drag. But the minimum consumption per h.p. hour will be about 7 per cent. less than at the lower speed, so that the consumption of fuel per air-mile will be only 35 per cent. more than the consumption at the most economical speed. If the wing area is decreased, other things being equal, the minimum drag will be greater, but the increase of drag with speed will be less, so that at high speeds the range will be greater than that of a more lightly loaded aeroplane. How far it is desirable to decrease the wing area in order to get better economy in flight at high speeds depends upon the answer to two practical questions. Firstly, what is the highest velocity of wind which one must take into account in organising a regular air transport service, and secondly, what is the minimum speed over the ground at which an aeroplane becomes a reasonable method of transport. Indeed, the effect of the wind on the actual range of an aeroplane and on the weight of fuel that must be carried to complete a certain distance over the ground is so great that although calculations of the maximum range of an aeroplane in still air have a certain interest of their own, particularly in connection with record long flights, yet one may say that the interest is largely academic.

If R_v is the range in air-miles of an aeroplane at any indicated air-speed, the range over the ground, if the velocity of the wind is v, is $R_v \times (V + v)/V$, v being counted as positive when the wind is a following one, and as negative in the case of a head wind. As the air-range is a function of the indicated air-speed $\sigma^{\frac{1}{2}}V$, not of the true speed V, it is strictly more correct to write this expression in the form

$$R_v \left((\sigma^{\frac{1}{2}}V + \sigma^{\frac{1}{2}}v)/\sigma^{\frac{1}{2}}V \right)$$

This brings out the fact, not always realised, that in deciding the best height to fly on a particular day, the point of interest is the variation of $\sigma^{\frac{1}{2}}v$ (which we might call the indicated wind-speed) with height, and not the variation in the speed itself. For this reason it would be better if meteorological observations of the velocity of the wind were always expressed in terms of $\sigma^{\frac{1}{2}}v$. If, for example, on any particular day the true velocity of the wind remained constant between heights of two and five thousand feet, it would pay to fly high when travelling against the wind, and to keep low when travelling with the wind. If the wind velocity only increased in inverse proportion to the square root of the atmospheric density, height would have no appreciable effect on the range either with or against the wind. There are quite a number of days when this occurs; but on the average the wind above about 2,000ft. increases in velocity with height inversely as the density—*i.e.*, σv is constant—so that on the average the ordinary rule holds that one should fly low against a head wind and high with a following wind. But it is very important to remember that this rule only applies when the rate of fuel consumption of the engine is the minimum possible. In view of the fact that it usually pays to keep low against the wind, altitude controls to carburettors are sometimes omitted. If no control is fitted, fuel is always wasted by flying high, whether the wind is favourable on contrary. The rate of consumption per h.p. increases inversely as $\sigma^{\frac{1}{2}}$, so that the consumption of fuel in lbs. per ground mile in a following wind is proportional to

$$D \times (C/\sigma^{\frac{1}{2}})/\eta \times \sigma^{\frac{1}{2}}V \div (\sigma^{\frac{1}{2}}V + \sigma^{\frac{1}{2}}v)$$

$$= D \times C/\eta \times \sigma^{\frac{1}{2}}V \div (\sigma V + \sigma v)$$

and this increases with height even if σ is constant. The absence of an altitude control prevents any advantage being gained from flying high; it does, therefore, seem of considerable importance to develop either some simple form of petrol flow-meter which will make the use of altitude controls easier; or, better still, to develop some system which will make the use unnecessary. By high flying in this connection, I am contemplating heights up to 10,000 feet or so. For many indirect reasons it does not pay, and perhaps never will pay, to consider greater heights for aerial transport except over mountainous country, where the conditions are different.

What is the most economical air-speed if the velocity of the wind is v? It is the speed at which $R_v \times (V+v)/v$ is a maximum. It depends, therefore, on the relation between R_v the range through the air, and the indicated air-speed of the aeroplane. It differs, therefore, from one machine to another, so that it is impossible to give a general answer to the question.

But before attempting to consider a case of interest for commercial flying, it may be of interest to point out some general conclusions which can be derived directly from the equation. At high speeds, above 2.3 V_0, the total drag (body and wings together) varies practically as the square of the speed. In this case the most economical speed to fly in a head wind, of velocity v, is 1.5 v. Thus, if the minimum speed of an aeroplane is fifty miles per hour, then an air-speed of 120 miles per hour will only be the most economical speed when the wind is eighty miles an hour, which does not often happen. Hence it is never necessary for economical flight to develop aeroplanes which have a great range of speed. For economy in flight one never wants a maximum speed as great as 2.3 times the minimum speed; this gives an indication at once of the necessity for aeroplanes of high loading, and of the fact that the higher the economic speed required, the higher must be the loading. The conclusion may, however, have a practical application of some interest in connection either with very light aeroplanes or with airships, or with military aeroplanes, which may have to operate at great heights and at very high air-speeds. One can conceive exceptional occasions to arise when it might be useful to bear in mind this relation between economical air-speed and the wind-speed in exceptionally high winds.

In the region when the drag is roughly proportional to the speed, the economical air-speed will be twice the velocity of the wind in the case of a head wind, and finally, in the range when the drag is approximately constant, the most economical speed in a head wind is obviously the highest speed of the range.

We must now return to consider the two questions propounded above. It is far more important to get fuel economy at high speeds than at low speeds, for two reasons. Firstly, the size of fuel tanks depends on the length of journey it is proposed to cover against the highest probable wind; once this decision is taken, diminution in fuel consumption due to more favourable weather conditions does not really affect the commercial load, since half empty fuel tanks are not convenient receptacles either for passengers or goods. Secondly, an aeroplane spends the greater part of its life flying against the wind, not with it. If the wind along the line of flight is 40 m.p.h., a commercial aeroplane will take twice as long to cover the distance in one direction as in the other, and will use three or four times as much fuel. Under these conditions a saving of 3 per cent. in fuel consumption at high speeds is equivalent to a saving of 10 per cent. at low speeds. Hence, so far as its performance is concerned, the design of an aeroplane to operate over any route must depend on the variations in wind velocity over the route.

Table II. contains data of the velocity of the wind at 1,500 feet in the neighbourhood of London, deduced from meteorological records spreading over the last thirty-five years. In Fig. 5, these results are plotted to show the percentage of days on which the wind is under a certain velocity.

TABLE II.

GEOSTROPHIC WIND AT LONDON: YEARS 1881-1915.

Frequency of Strength and Direction at 1,500 feet.

Estimates based on the D.W.R. Chart (8h., 1881-1908; 7h., 1909-1915).

Direction.	8½-16½ m.p.h.	16½-27½ m.p.h.	27½-38½ m.p.h.	38½-49½ m.p.h.	Over 50 m.p.h.	Total Frequency of Direction.
N.	259	250	212	89	77	887
N.E.	203	317	195	66	29	810
E.	136	322	251	108	36	853
S.E.	234	240	103	45	16	638
S.	248	330	168	94	66	906
S.W.	379	691	555	294	174	2093
W.	277	835	803	424	256	2595
N.W.	275	468	384	184	83	1394
Total frequency of strength ...	2011	3453	2671	1304	737	10176*

*Indeterminate 2,606, thus accounting for the 12,782 days of the years 1881-1915.

Taking the average over the whole period, summer and winter, we see that on 87 per cent. of the days the velocity of the wind at about 1,500 to 2,000 feet is under forty miles per hour. There are great differences, however, between summer and winter, the best month for light winds being July, and the worst month being December. In 97 per cent. of July days the wind is under forty miles per hour, but in December only about 70 per cent. The practical question arises, what is the minimum percentage of days on which one should aim at completing the full distance, without landing and taking in further fuel, to maintain a reasonably regular transport service? In the present state of air transport service, this question is a little difficult to answer. I think the proper point to take is the point at which the curve begins to bend over fairly sharply, such as the point marked A on the average curve. In the winter months it may be necessary to provide for fuel to contend with a wind of at least fifty miles per hour; but in the summer months it is only necessary to cater for a wind up to forty miles per hour.

To get the greatest fuel economy against a wind of 40 m.p.h. the aeroplane should be designed so that at the most "economical" speed the drag of the wings is a minimum. Call this minimum drag D_1. Let the body drag at a speed of 100 m.p.h. be D_2; then at a speed of V m.p.h. it will be $D_2 \times (V/100)^2$, and the total drag will be $D_1 + D_2 (V/100)^2$. The fuel consumption per ground mile will therefore be proportional to

$$\{ D_1 + D_2 (V/100)^2 \} \, V/V - 40$$

The value of V to make this expression a minimum depends upon the ratio D_1/D_2. When

$$D_1/D_2 = 0.64 \quad V = 80 \text{ m.p.h.}$$
$$D_1/D_2 = 1.0 \quad V = 87 \quad ,,$$
$$D_1/D_2 = 2.0 \quad V = 100 \quad ,,$$

Now the value of D_1/D_2 for the average machine, to which Fig. 4 refers, is 0.64; the value for the best commercial machine existing to-day is about 1.0; and it does not seem at all likely at present that the body drag will be reduced so substantially in practice as to make D_1/D_2 as great as 2.0. If, then, the aim is to design an aeroplane to consume the least amount of fuel in travelling a

certain distance over the ground against a 40 m.p.h. wind, then at present it must be so designed that the wings have a maximum L/D at a speed of about 85 m.p.h.; this is the "most economical speed." In the case of R.A.F. 15 wings, the speed at which L/D is a maximum is 1.7 times the minimum speed; so the latter will be 50 m.p.h., and the corresponding loading is 7 lbs. per square foot.

It is clear from the shape of the curve in Fig. 4 that the wing drag does not change very much over a fairly wide range of V/V_0 near the minimum point; this allows a considerable variation in the loading, without affecting very much the fuel consumption at the economical speed. But if the variation is carried too far the effect on fuel consumption will be considerable. For instance, the fuel consumption of an aeroplane loaded to $3\frac{1}{2}$ lbs. per sq. ft. ($V_0=36$) against a head wind of 40 m.p.h. will be about 20 per cent. greater than if the loading

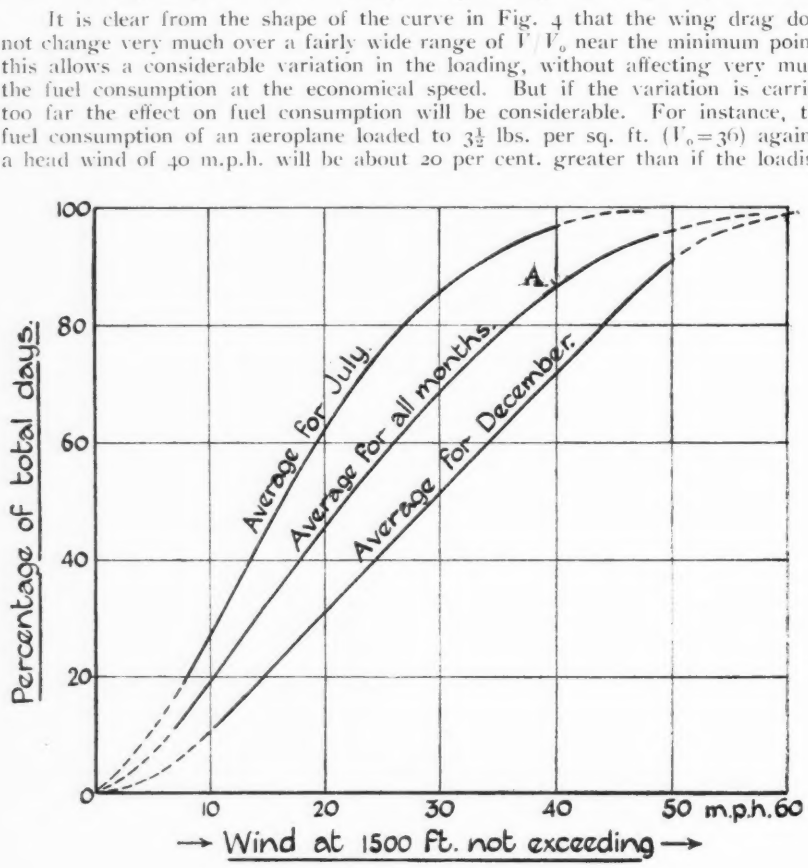

FIG. 5.

were 7 lbs. per sq. ft. For this reason I think that very lightly loaded aeroplanes, though amusing for sporting purposes, will not be suitable for getting from place to place. Unless and until there is a big revolution in design, the light aeroplane for private use should be loaded only so much less than 7 lbs. as is necessary to secure a slow landing speed, and should have a maximum speed not less than 85 m.p.h. If slow landing is secured by a special device, then the higher loading is indicated for economy.

But though a maximum speed of 85 m.p.h. may be suitable for ordinary pleasure flying, and for special private purposes, it is not high enough for commercial air transport—at least for passenger traffic. Air transport is of no advantage unless it can exceed in speed other forms of transport. The com-

petition varies in different parts of the world; but near at home the reasonable view to take is that the speed over the ground should be at least that of an express train, even in adverse weather conditions.

Let us assume, therefore, that the highest cruising speed must be 60 m.p.h. greater than the highest wind likely to be encountered. If we consider provisionally winds not exceeding 40 m.p.h., this means that the "cruising" speed of the aeroplane must be at least 100 m.p.h. This is, indeed, the accepted figure to-day. But one must note that, if sufficient fuel capacity is only provided for a forty-mile-per-hour contrary wind, then it will only be possible to go the full distance on about 70 per cent. of the days in the worst months of winter. In the case of a particular route, however, this conclusion will have to be modified. The curve in Fig. 5 does not take into account the direction of the wind; it simply represents the velocity of the wind in any direction. The general direction of flight on the London-Paris route is about south-east. If we examine the distribution of the direction of the wind in the worst months, we find that in December, of the winds over forty miles per hour, 29 per cent. are in a south-westerly or north-easterly direction, or shall we say, outside an angle of 68° to the line of flight; 38 per cent. are in a westerly or easterly direction, that is to say, between 22° and 68° to the line of flight. This accounts for the majority of the winds. Only 14 per cent. are south-easterly or north-westerly winds, that is to say, actually along or nearly along the line of flight. Now at a cruising speed of 100 miles per hour the wind velocity at right angles to the line of flight has to be as high as eighty miles per hour before it is equivalent to a forty-mile-per-hour head wind, and hence, for all practical purposes, in the case of the London-Paris route one

TABLE III.

Frequency of Strength and Direction of Wind at 1,500 feet.

DECEMBER.

Direction.	8½-16½ m.p.h.	16½-27½ m.p.h.	27½-38½ m.p.h.	38½-49½ m.p.h.	Over 50 m.p.h.	Total Frequency of Direction.
N.	7	20	14	17	9	67
N.E.	4	14	10	2	3	33
E.	5	19	15	8	2	49
S.E.	23	29	15	7	5	79
S.	21	26	22	20	16	105
S.W.	22	53	76	64	27	242
W.	13	43	72	82	33	243
N.W.	15	20	35	20	15	105
Total frequency of strength ...	110	224	259	220	110	923*

*Indeterminate 162; thus accounting for 1085, *i.e.*, 35 × 31 days.

need not take into account the south-westerly winds over forty miles per hour in estimating the number of days on which it would be impossible to complete the distance if fuel was only provided for a forty-mile-per-hour wind. The equivalent velocity for other directions of wind is shown in Fig. 6. In fact, if one takes fully into account the direction of the wind on the London-Paris route, one finds that only on 11 per cent. of the days, instead of 28 per cent., in the month of December is the wind velocity higher than that corresponding to a forty-mile-per-hour head wind. On the remaining number of days on which the wind is equivalent to a greater than forty-mile-per-hour head wind, a number may be, at present, unsuitable for flying for other reasons than the actual strength of the wind; so that it is probably reasonable, in the present state of flying, to provide for a head

wind not exceeding forty miles per hour in deciding on the amount of fuel necessary to complete the distance from London to Paris.

But the case would be very different if a regular flight in an easterly or north-easterly direction was contemplated. Then it would appear from the figures that it would be necessary to provide for winds of a velocity of fifty miles per hour in

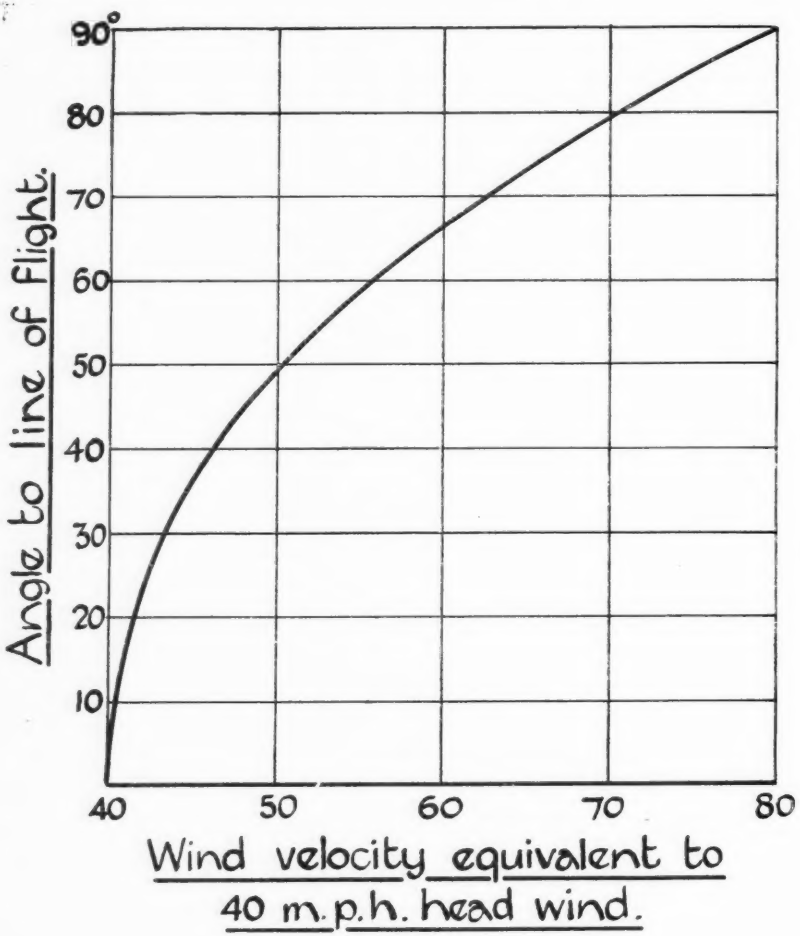

FIG. 6.

order to ensure a regular service in winter; and the highest "economical speed" would have to be 110 m.p.h. instead of 100. The necessity of providing engine power greater than that necessary to secure the highest economical speed is three-fold; firstly, to secure engine reliability; secondly, to secure a sufficient angle of climb from the ground; and thirdly, to secure a maximum indicated air-speed of 100 m.p.h. at greater heights in certain conditions of the weather. The over-riding necessity at present is that of engine reliability. No engine is yet capable

of being run for long periods at more than 90 per cent. of its maximum rate of revolution and more than 80-85 per cent. of its maximum torque without undue risk; and if it is under these conditions that the highest cruising speed of 100 m.p.h. is reached, the angle of climb off the ground will be sufficient even if the airscrew is designed to give maximum efficiency at cruising speeds, which must clearly be the aim if the greatest economy is sought.

Having, then, decided that the highest cruising speed must be at least 100 miles per hour, it is important to provide that the drag of the aeroplane shall be as low as possible under these conditions. Since the minimum drag of the wings occurs at a speed = about 1.7 times V_0 (see Fig. 4), it is necessary in order to secure minimum drag of the whole aeroplane at 100 miles per hour, to fix the loading so that $1.7\ V_0 = 100$, *i.e.*, $V_0 = 59$—which corresponds to a loading of 9.6 lbs. per sq. ft. of wing area. Before accepting this simple conclusion entirely, one must take into account certain other considerations. The first is, that as the total weight of the aeroplane varies during flight, the *average* drag during flight at 100 miles per hour should be a minimum; hence the loading should be 9.6 lbs. per sq. ft. in the middle of the flight, not at the beginning. If the amount of fuel used is 10 per cent. of the weight of the aeroplane, which is about the extreme figure for the London-Paris route, then the loading at the beginning of the flight should be 5 per cent. more than 9.6 lbs., or, say, 10.0. This, therefore, is the correct figure for the design of a fully loaded aeroplane for most economical flight at 100 miles per hour. The longer the distance to be travelled, and the higher the wind, the higher must be loading for most economical results in flight.

But there are still other arguments that must be considered. The machines operating on the London-Paris route have both a greater and a less wing area than the above figure; hence there are advocates of high loading and low loading. Apart from the question of landing speed, one can imagine the arguments to be something like this. The advocate of the higher-loaded machine will say that by decreasing the wing area he decreases the structure weight, and can increase the commercial load without increasing the total weight of the machine, thus securing a lower fuel consumption per unit of useful load, although he is not working under what are aerodynamically the most efficient conditions. But the saving in weight due to decrease in wing area is not very great; the weight of the wing structure certainly cannot be taken as nearly proportional to the wing area. According to the statistical data compiled by the Air Ministry, the average weight of the wing structure of single-engined aeroplanes varies from about 14 per cent. of the total weight when the loading is 8 lbs. a sq. ft. to 12 per cent. when it is 14 lbs. per sq. ft.; but the variation from machine to machine is very considerable, and there are cases when the percentage weight of the wing structure is as low as 12, when the loading is 8 lbs. a sq. ft. It would appear to be rather an over than an under-estimate to state that a saving in the weight of the wing structure is 1 per cent. of the total weight of the machine, if the loading is 13 instead of 10.0. If we take this figure, it corresponds to a possible increase in the weight of the commercial load of 4 per cent.; but if the loading is 13, V/V_0 at the indicated air-speed of 100 m.p.h. is 1.45, at which point the wing drag is 6½ per cent. greater than the minimum wing drag. This corresponds, on one of the present-day machines, to a 3 per cent. increase on the minimum total drag, so that on these figures there is little to choose, from the point of fuel economy, between an aeroplane loaded at 10 and one at 13, while on the grounds of landing speed, rate of climb, and fuel economy at lower speeds, the lower loading seems to be very desirable.

On the other hand, the advocates of low loading (8-9 lbs. a sq. ft.) may say that it is true that increasing the wing area slightly increases the weight of the machine, and therefore may be taken as decreasing slightly from the commercial

load to be carried for the same total weight, but the increase in drag over the optimum figure is quite small, and, on the other hand, a better rate of climb is secured and a greater fuel economy at lower speeds than the maximum cruising speed.

On the whole, I think the advantage of the argument lies with the advocates of high loading, if we do not take into account the difficulty of the high landing speed; but in view of the difference of opinion between the expert designers, it is perhaps natural to suggest that a loading of 10 lbs. a sq. ft. is not only aero-

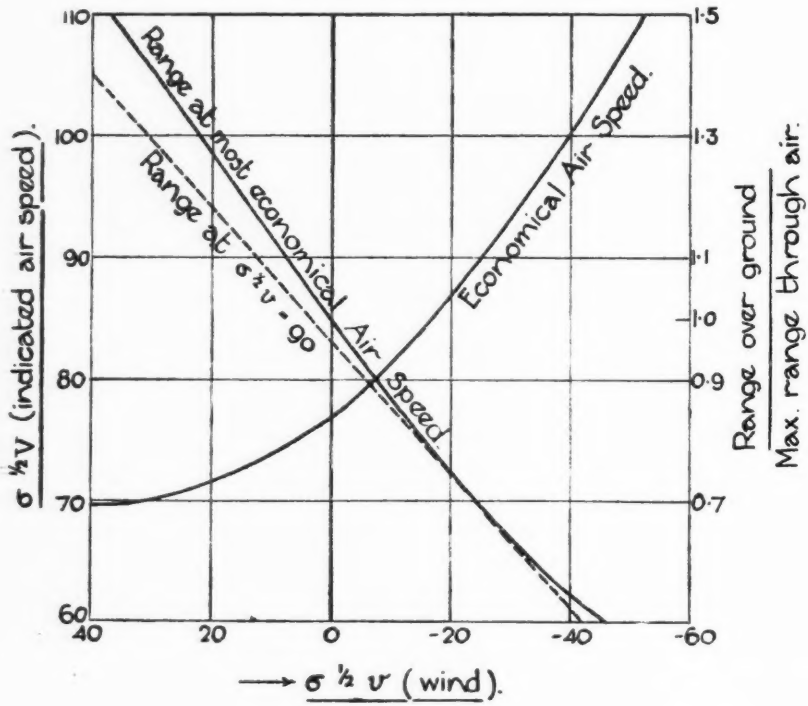

FIG. 7.

dynamically the most efficient, but also from a practical point of view the best compromise.

It will be worth while to make a calculation of the minimum amount of fuel which it will be necessary to carry for the London-Paris route under these conditions. For this purpose we have got to assume a figure for the body drag. Taking the wing characteristics given in Fig. 4 as correct, the body drag of the single-engined commercial machines of the present day seems to average, at 100 miles per hour, about 0.072 times the weight of the fully loaded aeroplane. Incidentally, this means that the curves given in this figure, although originally drawn for machines of a loading of 7 lbs., now apply very closely to modern commercial aeroplanes loaded to 10 lbs. a sq. ft. The total drag, then, of the fully loaded aeroplane will be 0.134 W at 100 m.p.h. The petrol consumption per h.p. hour will be practically the same as that at full power, namely, 0.52 lbs. for engines

of compression ratio 5 : 1. Taking an average propeller efficiency of 75 per cent., the petrol consumed per mile in the case of the fully loaded aeroplane should be not more than .0025 W, *i.e.*, the range at 100 m.p.h. should be as great as the *maximum* range of machines of the war period, the increase in efficiency being due to lower body resistance and better engines. Against a head wind of forty miles per hour, the petrol consumed will be .0025 W multiplied by 100/60 per mile over the ground, or for the 230 miles of the London-Paris route, the total consumption will be 0.096 W. This leaves a slight margin, since it refers to the fully loaded aeroplane, without taking into account the change in weight over the route. The corrected total will be about 5 per cent. less, namely, 0.091 W. Any aeroplane carrying a smaller amount of fuel than this will be unable to complete the distance without landing if the head wind is as high as forty miles per hour. Actually, of course, one has to provide a larger amount for safety and to cover what is known as "dead" flying. If we take the margin as 15 per cent., which should be ample, the total amount of fuel to be provided for would be 0.105 W, or just over one-tenth the weight of the fully loaded machine. In a similar way the range and the most economical air-speed in winds of different velocity can be calculated. Fig. 7 shows these results for the type of commercial machine considered above, the range being expressed as a multiple of the maximum range. It is of practical importance to note that a considerable error in selecting the most economical air-speed has only a small effect on the range. To illustrate this a dotted line has been drawn in the figure to represent the range at a constant air-speed of 90 m.p.h. It will be observed that though the most economical air-speed in a head wind of 10 m.p.h. is 80-85 m.p.h., the range at an air-speed of 90 is only 1 per cent. less than the maximum possible range. It is only in following winds that a reduction of speed below 90 m.p.h. has any substantial effect, the range at 90 m.p.h. with a following wind of 40 m.p.h. being 10 per cent. less than the maximum possible range which is reached when the air-speed is 70. All this assumes that the petrol supply to the engine is reduced to the minimum; if no compensating device is fitted, it is doubtful whether a reduction in speed below 90 m.p.h. ever pays, since, as previously stated, it is practically impossible to adjust a carburettor to give automatically the most efficient results except over quite a small range of torque.

It is of interest to consider in what directions we may look for marked improvements in the near future in economical flight. There does not seem to be any indication that airscrew efficiency can be substantially increased in practice. Maximum efficiencies of 80 per cent.—perhaps higher—can already be obtained. A higher average efficiency than is now achieved may come about as a result of further experiments on airscrew and body interference, but we have little to go upon at present to justify optimistic prophecies.

A reduction of drag may be effected in two ways—by the introduction of wings of higher efficiency, and by substantial improvements in "body" design. In recent years Prandtl's theory has given a new impetus to the general investigation of aerofoils, and we are now reaching a very interesting stage as the result of practical and theoretical work at the Royal Aircraft Establishment and the National Physical Laboratory. But I doubt whether we have actually reached the stage at which any definite pronouncement can be made as to the possibilities of a marked improvement in wing efficiency. Wing sections similar to R.A.F.15 seem likely to hold their own for some time. The latest experiments indicate a maximum lift/drag ratio of 21 for the single aerofoil and a minimum drag coefficient at small angles of incidence of 0.0065. The assumption has been made in this paper that in normal biplane construction the maximum L/D ratio is approximately 16, and the minimum drag coefficient is 0.008. Whether these figures are correct is uncertain; if they are incorrect, the only effect, so far as these considerations on fuel economy are concerned, will be to alter the absolute values of the figures quoted for body drag, without altering appreciably the relative

values. The modified wings fitted to the American Curtiss racing aeroplane have possibly a minimum drag coefficient as low as 0.005; but what interests us most in connection with economical flight is the maximum lift/drag ratio, and it does not necessarily follow that an increase in this ratio is obtained if a wing of lower minimum drag coefficient is introduced. There is a possibility that an increase in the maximum lift/drag ratio can be obtained by a sacrifice of the lift at high angles of incidence, *i.e.*, by increase in landing speed for wings of the same area, and that the latter disadvantage will be overcome by the adoption of one of the devices now under experiment for securing an abnormally low landing speed by altering the shape of the wing at high angles of incidence. There are also possibilities in the direction of the development of thick wing sections; but some of the claims which have been made in this connection, as a result of experiments in other countries, seem too good to be believed without much more definite evidence. On the whole, I think it would be right to say that in the present state of knowledge it is impossible to pronounce either for or against the likelihood of a considerable increase in wing efficiency under conditions which affect the economy of air transport. When we come to consider body drag, we are on firmer ground. It has long been realised that there are certain methods by which great improvements could be effected if the purely engineering difficulties could be overcome. Some method of withdrawing the undercarriage into the main body during flight is badly wanted if it can be done without adding weight which will more than counterbalance the drop in resistance. The substitution of wing-radiators for the frontal radiator, which accounts for a substantial part of the total body resistance, has already been accomplished successfully—unfortunately in other countries. Scientific investigation into the most efficient form of radiator for aircraft purposes has hardly received the attention it deserves in this country in the last few years; it is fortunately now being taken up again. But apart from these questions, our knowledge of the best shape of the fuselage of an aeroplane is still very incomplete. If I may quote a recent remark of Professor Bairstow, no scientific data exist on the best length for a body of a given maximum cross-section. Length of body has probably been fixed, consciously or subconsciously, by analogy with birds; but a bird's body has no doubt been evolved gradually as the best compromise between aerodynamic and physiological efficiency; and since the internal organs of aeroplanes and birds differ considerably, it does not follow that the imitation is sound. Experimental work in this direction may lead to results of great importance for the future of air transport. Even now we have some definite facts to go on. It has already been said that the body drag of the modern commercial aeroplane averages about 0.07 times the weight of the fully loaded machine at a speed of 100 m.p.h. The most efficient commercial machine has a body drag of about 0.06 W at the same speed. The Curtiss racing machine has a calculated body drag of 0.02 W, if we assume the airscrew efficiency to be 80 per cent. and the wing characteristics to be those given above in Fig. 4. Even if the minimum wing drag coefficient were as low as 0.005, the body drag at 100 m.p.h. would only be 0.03 W, or half that of the most efficient British commercial machine. It may be justly pointed out that a comparison made on the basis of the weight of the machine is hardly fair, since the drag/weight ratio depends on how closely the engine, fuel tanks, pilot and other load can be packed inside the body, and a racing machine can be packed closer than a commercial machine carrying passengers. On the other hand, it must be remarked firstly that this particular racing machine had an engine of approximately the same power and dimensions as the commercial machine we are considering, and therefore that the cross-sectional area of the body of this comparatively light machine (2,100 lbs.) was necessarily large; and secondly, that the bigger the size of an aeroplane the lower should be the ratio of body drag to weight for the same density of packing. Both these considerations favour the commercial as compared to the racing aeroplane. I hardly think, therefore, that it is unduly optimistic to look forward in the near future to

a reduction in body drag of a commercial aeroplane to as low a figure as 0.04 lb. at 100 m.p.h. This would be a 40 per cent. reduction in body drag on the figure taken to represent the present average, and would correspond to a 24 per cent. reduction in the total drag at 100 m.p.h., if there is no improvement in wing efficiency. At higher speeds the reduction would be still greater.

When this happy time arrives we shall be confronted with an interesting problem. At present, as has already been said, an aeroplane whose engine operates at under 85 per cent. torque and 90 per cent. speed at a level air-speed of 100 m.p.h. has just sufficient reserve power to provide for a reasonable rate of climb at ground level even if the airscrew is designed to give maximum efficiency at the cruising speed. But if the body drag is reduced by 40 per cent., this will no longer be true; and either the power of the engine will have to be sufficient to give a much higher maximum speed, or some other means will have to be adopted to improve the rate of climb, *e.g.*, by a variable wing, or by sacrificing airscrew efficiency at cruising speed, or by the use of a fuel such as alcohol, which gives a higher torque than petrol, for climbing purposes. It will be wise to prepare for these eventualities beforehand. The object of pointing them out now is to show that it cannot necessarily be assumed that a substantial decrease in body drag will also mean a corresponding decrease in engine power and weight.

Finally, engine developments are now approaching a stage of great importance for aircraft purposes. The multi-cylinder internal combustion engine suffers under two great disadvantages—(*a*) that owing to imperfect distribution some cylinders are always being supplied with a considerably richer mixture of fuel and air than others, and (*b*) that it is impossible to explode completely in the short time available a mixture which contains more than about a 15 per cent. excess of air. The greater the excess of air, the higher is the thermal efficiency of the process; and the net effect of these two disadvantages is, therefore, that a multi-cylinder engine has in practice a much lower efficiency than can be obtained from a single cylinder of the same size and compression ratio. A general scientific attack on the problem of the induction system of aircraft engines holds out little hope of success; the problem is so complicated that it must be studied separately for each type of engine. It becomes simpler when the induction system is symmetrical, as in the case of radial or rotary engines, but these engines have other practical disadvantages for commercial purposes. The lowest petrol consumption of a multi-cylinder engine of compression ratio 5 : 1 is approximately 0.52 lbs. per h.p. hour; while the lowest consumption observed on a single-cylinder engine of the same compression ratio is 0.48 lbs. per h.p. hour. If it were possible to explode a petrol-air mixture in presence of excess of air, these discrepancies would disappear; more than that, the thermal efficiency would increase as the torque diminished, if the reduction in torque was effected simply by reducing the petrol supply and keeping the air supply constant, instead of by reducing the whole density of the charge by throttling, as is the present practice. The necessity for altitude controls to obtain the highest economy would also disappear. Only two practical methods of securing these advantages have been suggested. One is the method of direct injection; but although experiments in this direction have yielded very interesting results, it is, in my opinion, still very doubtful whether engines of this type will be found suitable for heavier-than-air machines. The other is the method of stratification. The principle of this method is to avoid complete mixing of air and fuel vapour inside the cylinder, and so to arrange matters that the sparking plug is surrounded after compression by a rich mixture, while in the region nearest the piston air is present in excess of the amount necessary for complete combustion of the fuel. Under such conditions a rapid explosion results, followed by complete mixing, and the excess air keeps the flame temperature and dissociation down. The theoretical advantages of such a system have long been recognised, but the practical difficulties have hitherto seemed insuperable. Recently Ricardo, who has pursued this line of inquiry with a persistence worthy of success, has evolved

a method which appears to be both simple and effective. This is not the occasion to enter into details; I must content myself with quoting the results. The preliminary experiments have indicated that with compression ratios of 5 : 1, a rate of consumption of 0.45 lbs. per b.h.p. hour may be possible at cruising speeds. With a single cylinder unit of compression ratio 6.2 to 1, a fuel consumption of 0.4 lbs. per b.h.p. has been observed, with little variation over a range of torque corresponding to the range of a commercial aircraft engine. The method of obtaining stratification favours the use of somewhat higher compression ratios than those at present in use; and there is no reason to doubt that similarly good results can be obtained with multi-cylinder engines of a size suitable for commercial aeroplanes. In the simplest form, an engine working on this principle will be only slightly more economical in fuel than the ordinary engine when full power is being developed; the big reduction in rate of consumption occurs when the fuel supply is not sufficient to develop more than 90 per cent. of the maximum torque. But full power is only necessary for short intervals, *e.g.*, in climbing, so that this is a matter of no great consequence.

It is then in the directions of lowering body resistance and of developing engines of greater economy in fuel consumption that there appears to be the most immediate possibilities of a marked improvement in the economy of flight. Without taking any account of possibilities in other directions, which have hardly emerged from the chrysalis stage, but attaching weight only to results in sight, we may look forward without undue optimism to the development of commercial aircraft in the next few years which have a 25 per cent. less resistance at 100 m.p.h. than those at present in existence, and are fitted with engines of 20 per cent. higher thermal efficiency at cruising speeds. The net effect would be that the range with a given amount of fuel would be nearly doubled, or that for a short range of 250 miles against a head wind of 40 m.p.h. the commercial load could be increased by over 20 per cent., and the cost of fuel reduced by over 40 per cent.

Looking at the whole subject dispassionately, and indeed critically, as I have been forced to do in the preparation of this lecture, I feel confident that, given continuity of effort and a due appreciation of the value of scientific investigation in this most scientific industry, there are no grounds for discouraging the popular belief that before many years have passed, aerial transport will be as commonplace as it was marvellous twenty short years ago, when Wilbur Wright made his first memorable flight.

ASSOCIATE FELLOWSHIP EXAMINATION

Aerodynamics

Time Allowed—Three Hours. Answer SIX Questions Only.

1. Describe and indicate the theory and uses of :—

   either The Accelerometer,

   or The Aerodynamic Turn Indicator.

2. Discuss in detail the function of the elevators in varying the speed of an aeroplane in straight flight. Show that for steady motion without side-slip in a horizontal circle the elevator setting will differ from that for straight, level flight at the same speed.

3. Explain the meaning of the term " damping factor " as applied to an oscillation of an aeroplane. Briefly set out the details of an experiment to determine this quantity approximately in the case of pitching. How would the damping depend on speed?

4. Write down a formula connecting lift with velocity and " circulation," and, taking the case of an aerofoil completely spanning the section of a wind channel, explain how you would verify it experimentally.

5. At ground-level (kinematic viscosity = 0.00016) the drag of 4ft. run of tubing of a certain section, 2ins. in maximum width, is found to be as follows :—

Airspeed	...	20	30	40	50	60 ft. per sec.
Drag	...	0.18	0.33	0.63	1.03	1.51 lb.

   Find the drag of 7ft. of tubing of similar section but 0.6in. in maximum width at 10,000ft. altitude (density = 0.00175, kinematic viscosity = 0.00020) and an indicated airspeed of 100 m.p.h.

6. As a result of reducing body resistance, the maximum speed of an aeroplane weighing two tons is increased from 86 to 93 m.p.h. The landing speed is 41 m.p.h., the thrust horse-power developed is 260, and the wing system is known to yield the following test figures :—

Lift coefficient	...	0.1	0.2	0.3	0.4	0.5 (max).
Lift/drag	...	8.5	14.2	13.7	10.9	6.0

   Estimate the improvement in the max. ratio of climb at ground-level.

7. For what uses are ballonets fitted to non-rigid airships? Briefly describe their arrangement and working.

8. Show how the effect of a steadily increasing head wind may be allowed for in reducing the true rate of climb from observations.

   The rate of climb of a certain aeroplane is as follows :—

Altitude (ft.)	Ground	5000	10000	15000	20000	25000
Rate of climb (ft. per min.)	1600	1300	1070	700	470	330

   Find the time required to climb to 25,000ft.

9. Define the " experimental mean pitch " and the " slip " of an airscrew. With the help of curves, describe the effects of varying pitch diameter ratio. Hence discuss the advantages of a variable pitch airscrew used with a supercharged engine.

Strength of Materials and Theory of Structures

Time—Three Hours. Attempt EIGHT Questions Only.

1. Explain clearly why Clapeyron's theorem of three moments requires modification when applied to the spars of an aeroplane of normal biplane construction.

2. A cantilever of length L is square at every cross section and tapers uniformly from the root to the tip. The side at the root is S_0 and at the tip is S_E. Find the deflection at the tip under a uniformly distributed load of W per unit length over the whole cantilever.

3. Discuss the various conditions of loading to which the fuselage of an aeroplane may be subjected.

4. Give Perry's approximate formula for the maximum bending moment in a laterally-loaded strut and state the assumption upon which it is based.

   A square beam is made of spruce 4ins. × 4ins. in section, and is freely supported over a span of 10ft. It carries an end load of one ton axially applied. Calculate the uniformly distributed lateral load it can support if the maximum permissible stress is 5,000 lbs. per square inch. E for spruce = 1.6×10^6 lbs. per square inch.

5. Describe with diagrams any tensile testing machine of the compound lever type with which you are familiar. Why is this type used instead of the single lever?

6. Describe the standard tests for silver spruce.

7. An encastré beam 40ft. in span carries loads of two tons and four tons at distances of 20ft. and 30ft. from the left-hand support. Calculate the values of the fixing moments at the ends.

8. A beam 30ft. long rests on two supports at its ends and carries a load of two tons 10ft. from one end. It is then propped in the middle of the span to the same level as the ends. What is the reaction on the prop?

9. What functions have the undercarriages of an aeroplane to perform? Discuss the nature of the loads to which it may be subjected.

10. Describe a method for finding the deflection of a joint in any framed structure carrying loads

    (*a*) When the structure is just stiff.
    (*b*) When the structure is redundant.

    Distinguish between the cases when the joint under consideration is loaded and when it is not.

Heat Engines

Time—Three Hours. Answers are not expected to more than SIX Questions.

1. A cylinder contains air at a pressure p_1 and absolute temperature T_1. It expands, doing work on a piston, to twice its original volume. What is the final temperature and pressure and the work done during expansion, if the expansion is (1) adiabatic, (2) isothermal? The ratio between the specific heats of the gas at constant pressure and constant volume is γ.

2. A heat engine receives a quantity of heat Q at absolute temperature t_1 and rejects its heat at an absolute temperature t_2. What is the maximum amount of energy that it can theoretically give out as mechanical work, and how much heat does it reject?

   Why is the internal combustion engine more efficient, as a rule, than the steam engine?

3. A perfect gas at a pressure p_1 and absolute temperature T_1 expands through a nozzle to a pressure p_2. Assuming adiabatic expansion and no losses in the nozzle, what is the temperature after expansion?

   If the velocity of the gas is then reduced by eddies, etc., without gain or loss of heat from external sources, to its value before expansion, what does the temperature of the gas become?

   Indicate briefly the conditions under which it is desirable to use (1) converging, (2) convergo-divergent nozzles.

4. Describe briefly the ideal cycle of operations of the constant volume engine with equal compression and expansion ratios. On what factors does the ideal efficiency of this cycle depend? Give the equation for efficiency. Indicate in what respects the practical constant volume cycle differs from the ideal case and the effect of these differences.

5. What is the characteristic of petrol which limits the compression ratio which can be employed at ground-level, and how is it influenced by the nature of the fuel? What are your views as to the effect of altitude on this limitation?

6. What is meant by "Air Standard Efficiency"? An engine operating on the Otto cycle has a bore of 5ins. and a stroke of 7ins.; calculate the clearance volume to give a compression ratio of six to one and find the Air Cycle Efficiency for this compression ratio. The value of γ may be taken as 1.41.

7. A six-cylinder engine, bore 5½ins., stroke 7ins., and compression ratio 6.25 to 1, is found on test to develop a torque of 900 lbs. feet at 1400 r.p.m. and to consume per hour 120 lbs. of fuel, having a heat value of 18,100 B.T.U.'s per lb. Assume a mechanical efficiency of 89 per cent. Calculate the indicated mean effective pressure, indicated thermal efficiency, friction h.p. and brake mean effective pressure, also efficiency relative to the air cycle efficiency for that compression ratio.

8. The crankshafts of six and twelve-cylinder petrol engines are frequently fitted with devices to damp out torsional oscillations of the shaft. Describe the sequence of events leading to the oscillating of an undamped shaft and explain the principle of a damper and how the presence of a damping device affects the behaviour of such a shaft.

9. Comment on the advantages and disadvantages attaching to the use of aluminium alloys for (*a*) pistons, (*b*) connecting rods, as compared with ferrous metals.

10. Why does a four-cycle radial engine generally have an odd number of cylinders per crank?

11. Discuss briefly the balancing of the following types of engines:—

    (1) Four-cylinder in line.

    (2) Six-cylinder in line.

    (3) Three-cylinder radial engine.

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